Thermo Electron Engineering Corporation, 85 First Avenue, Waltham, Massachusetts 02154

Contract No. 951263

Report No. TE 57-67

FOURTH QUARTERLY REPORT

SOLAR THERMIONIC

GENERATOR DEVELOPMENT

December 1966

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Prepared for

Jet Propulsion Laboratory
Pasadena, California

INTRODUCTION

This document constitutes the Third Quarterly Report on the work being performed under Thermo Electron's Contract No. 951263 with the Jet Propulsion Laboratory. The program is divided into two related tasks, and has for its objective the development of a multi-converter generator.

Task I centers on the iterative construction of nine engineering models of a solar-energy thermionic converter. The aim of the first model is to partially duplicate the best converter developed under Task II of Contract No. 950671. The second and third models are principally geared to the incorporation of a modification in the heat-transfer path of the collector-radiator structure to assure efficient and reliable heat transfer. The fourth and fifth models are intended to effect a change in the materials of the convoluted emitter structure whereby the entire structure will be made of rhenium. The sixth and seventh converters will provide a study of two new collector materials, and the eighth will be a final prototype incorporating all the features found to improve performance in the course of the work. The ninth prototype will be fabricated to demonstrate reproducibility of performance.

Task II involves a generator flux analysis, a shielding evaluation, and a mock-up environmental test based on a selected generator design. The analysis will determine the best number of converters to match the converter heat requirements to the available solar energy, the optimum cavity aperture size, the required adjustments of surface emissivity and absorptivity values to ensure even flux distribution, and the effects of changes in emitter temperature and heat input on flux distribution within the generator. The shielding test is primarily intended to verify design assumptions on shielding heat losses, and to select a preferred shield configuration. The mock-up environmental tests will be conducted to explore all areas of possible structural weakness to vibration, shock, acceleration and acoustical environments, and effect the design changes indicated.

This report covers progress for the period from September 4, 1966, to November 30, 1966.

SUMMARY

During the fourth quarter the fifth thermionic converter engineering model, T-205, was fabricated and tested. This converter had a design spacing of 4.2 mils instead of the spacing of 1.75 mils which had been used for model T-204. The performance of T-205 was lower than that of T-204, but the fact that Converter T-205 had to be outgassed and cesiated three times because of leak problems prevents concluding with certainty whether the difference in performance of these two models is solely the result of a change in spacing.

It was also found during this reporting period that the arc-welded rhenium tubing used for the fabrication of the all-rhenium support is often defective in the region of its seam weld. Consequently, efforts have been made to perform the seam welds of the tubes by electron-beam welding in the future.

Further fabrication work involved the construction of pressure-bonded rhenium collectors and the lapping of emitter surfaces.

Under Task 2, a preliminary analysis of generator performance has been completed, which indicates that, of the several multi-converter generator configurations studied (namely, those with 10, 12, 14 and 16 converters), the largest generator is preferable in order to assure that the generator cavity will be large enough to handle the flux delivered by an 11.5-foot mirror at the Table Mountain test site.

CHAPTER 1

1.1 Fabrication of Converter T-205

As explained on page 19 of the Third Quarterly Report, it was noticed that Converter T-204 had a collector temperature drop considerably higher than that previously achieved. This increase in collector temperature has been traced to the lack of direct heat transfer from the collector barrel to the radiator fins, and this was, in turn, due to an oversimplification of collector structure design. The design is shown in Figure 1. To obviate this difficulty, the collector barrel of Converter T-205 was designed to incorporate slotted sections that make effective contact with the radiator fins.

Two other important design changes were effected in the structure of Converter T-205. The first change was suggested by the JPL Technical Representative and was to increase the interelectrode spacing of the converter by 2 to 3 mils to a value approximately equal to 4.25 mils. The increase was accomplished by machining the face of the collector so as to leave a raised edge around the collector face 12.5 mils wide and 2 to 3 mils high. The second change was a very slight increase in the collector face diameter, so that the spacing between the cylindrical edge of the collector and the sleeve supporting the emitter would be of approximately the same magnitude as the interelectrode spacing (that is, approximately 4 mils), and it would therefore be more nearly possible to optimize the operating conditions in the interelectrode spacing and at the collector periphery simultaneously.

In order to preserve the dimensional tolerances of the raised edge on the collector face of Converter T-205, the collector surface was not chemically etched, as had been those of Converters T-203B and T-204. As in Converter T-204, the emitter of Converter T-205 is a slab of rhenium 0.060" thick, which, in the case of Converter T-205, was found to be concave by 0.0007". This is somewhat more than the 0.0003" and 0.0004" out of flat that had been previously recorded in the First Quarterly on page 38. The slightly larger deviation from flatness of the emitter of Converter T-205 is not serious, however, because of the much larger interelectrode spacing. The deviation from flatness may be the result of thermal relief of the grinding stresses locked in the relatively thin rhenium slab.

In all other respects, Converter T-205 was nearly identical to Converter T-204, and it includes radiator fins coated with chromium carbide.

1.2 Outgassing of Converter T-205

The first outgassing of Converter T-205 was applied for 65 hours. The converter was then cesiated according to normal procedures and set up for testing. When the converter was first warmed up for test, it became immediately apparent that there was an air leak, and testing was stopped. A leak check quickly showed that the converter had a leak at the pinch-off. Further investigation to determine the cause of this leak revealed that the copper tubing used for exhausting the converter had been polished with emery cloth in the machine shop as a final polishing operation. Normally, a copper tubing is not given this polishing but is used with the as-received finish of

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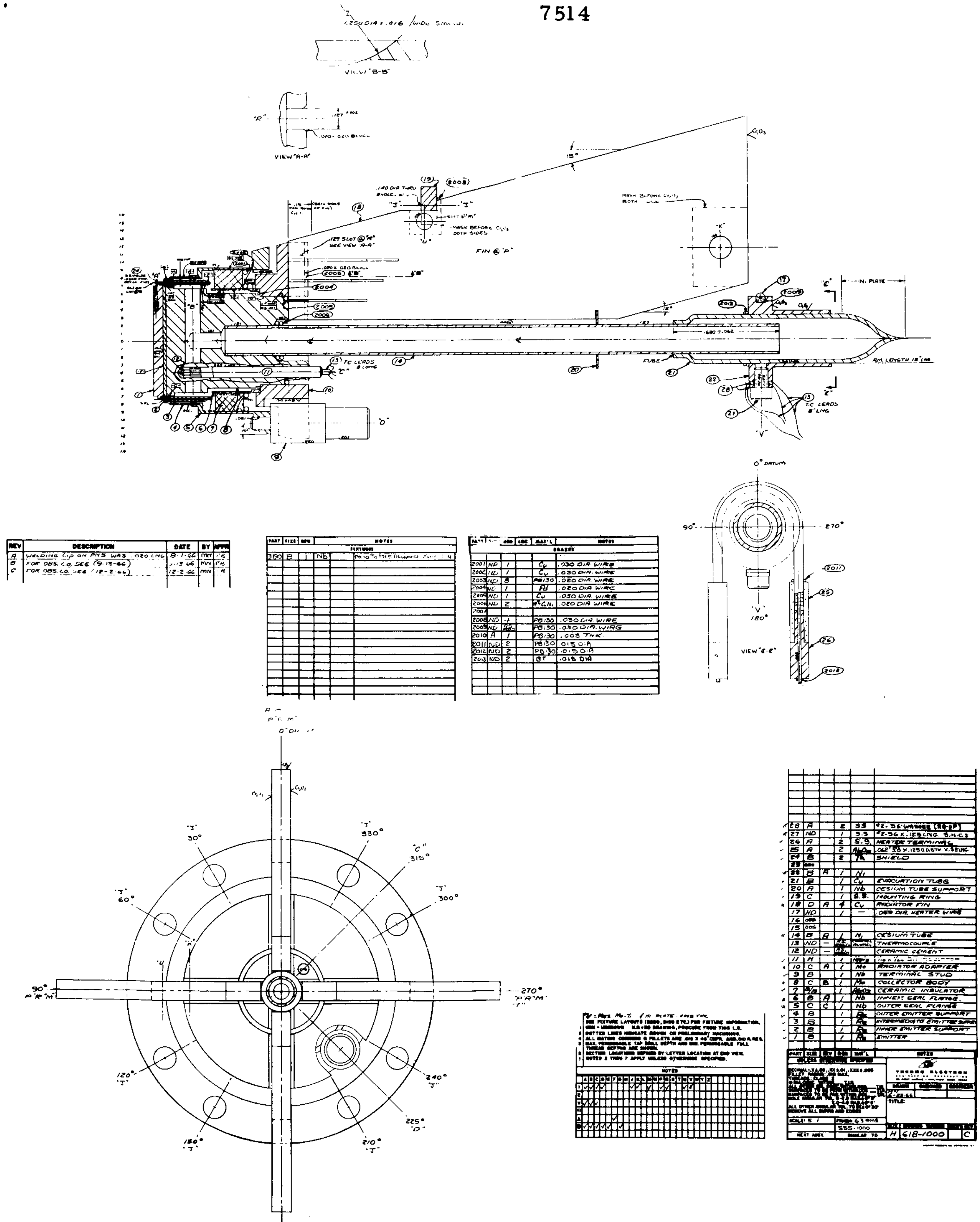


Figure 1

the outside surface. A microscopic examination of the copper material near the pinch-off showed that emery particles had remained embedded in the copper and very likely had interfered with the pinch-off operation. To clean the converter from whatever contamination may have resulted from the air leak, it was placed overnight in a furnace at 600° to 700°C after removal of the defective pinch-off. A new copper tubulation was brazed, and the converter was set up for a second outgassing. The outgassing was performed for a total outgassing time of 68 hours. It was then pinched off and cesiated. When attempts were made to test the converter, it was again discovered that an air leak had developed. The leak was found at the same location, namely, at the pinch-off of the cesium reservoir. To diagnose the cause of this leak, an examination was made of the portion of copper tubing that had contained the cesium capsule from which cesium was distilled into the converter. The inside wall of this tubing was found to be completely blackened. A portion of the tubing was then cut and rf-heated in an open bucket in vacuum at gradually increasing temperatures to observe the behavior of this black coating with increasing temperature in vacuum. It was sustpected that this coating was cupric oxide, and, indeed, at about 600°C it turned to the characteristic reddish color of cuprous oxide and pure copper. It was subsequently reasoned that this copper oxide had formed during the second outgassing, when more oxygen was released by the converter while the outgassing tubulation was relatively cold and in the temperature range which would readily cause oxidation. With an oxidized inside wall, it was then impossible to perform a successful pinch-off. This then implied that the heating of the converter in vacuum in a furnace at

600° to 700°C overnight had not been sufficient to remove the oxygen within the converter. To improve upon this procedure the converter structure was then set up in its outgassing stand rather than the vacuum at typical outgassing conditions with the pinch-off removed, so that all oxygen could then be released from the surfaces heated at their normal operating conditions. After this treatment a new tubulation was brazed in place, the converter was given a further outgassing of one hour, and it was cesiated for two hours with the cesium ampoule at 200°C. Subsequent attempts to test the converter showed that the repair had been successful.

1.3 Testing of Converter T-205

Converter T-205 was tested following the procedures outlined in JPL Engineering Note ADEN 342-005.

The relative collector work function measurement indicated no change over a period of 56 hours, as may be observed in a comparison of the volt-ampere traces 1 and 22, which are appended. The voltage measured at an output of 40 amperes, for a collector temperature of 1042°K and a reservoir temperature of 680°K, was 0.61 V, and it is the lowest recorded so far in this program. This could be the result either of an increase in interelectrode spacing to 4 mils, or of contamination of the converter structure in the two instances when an attempt was made to operate it after an air leak had developed. In the optimized 144-hour run, which was limited to 26 hours so that other testing could proceed, the performance observed for Converter T-205 is shown below, compared with that of the other four converters built under the program.

	T-201	T-202	T-203B	T-204	T-205
Emitter temperature, °K	2000	2000	2000	1974	2000
Output voltage, V	0.60	0.80	0.80	0.77	0.77
Output current, amperes	38.0	43.4	39.3	41.4	49.3
Reservoir temperature, °K	623	621	614	618	614
Collector temperature, °K	1030	1006	979	1074	1043
Power input, watts	302	297	299	323	362
Collector temperature drop, °C	223	213	177	260	283

Although it appears from the above tabulation that the performance of Converter T-205 is superior to that of T-204, this impression is, in vact, the result of operation at a higher emitter temperature. A more accurate performance comparison is presented below. Since Converter T-205 had a tendency to operate at high collector temperature, its radiator surface was increased by means of four additional fins mechanically fastened to the converter radiator. This is the reason why, in the above tabulation, Converter T-205 also operates at a lower collector temperature in spite of its higher output current. The additional fins were also used when obtaining the I-V characteristics of T-205, but were removed before the final steady-state run at 1.0 V in order to conform with ADEN 342-005, which specifies that in this run no additional cooling or heating of the collector is to be used.

The fully optimized I-V curves at 2000°K show the following differences in converter output current (amperes):

	T-201	T-202	T-203B	T-204	T-205
0.8 V	28.3*	43.5	40.0	45.3	41.0
1.0 V	20.8*	14.2*	23.2	26.0	22.1
1.2 V	14.6*	10.0*	18.1	18.5	12.8

The steady-state performance achieved with the various prototypes at an output voltage of 1 volt, with no heat applied to control collector temperature, and with optimized reservoir temperature, is as follows:

Prototype:	TE-103	T-201	T-202	T-203B	T-204	T-205
Hohlraum temperature, °C	1723	1700	1700	1700	1724	1720
Output current, amperes	32.5	14.8	12.3	17.6	29.0	17.1
Reservoir temperature, °K	614	602	592	614	614	590
Collector temperature, °K	1015	886	852	865	1002	928
Radiator temperature, °K	—	737	720	739	802	758
Collector temperature drop, °C	—	149	132	126	200	170
Power input, watts	282	220	202	226	292	257
Overall efficiency, %	11.5	6.7	6.1	7.8	9.9	6.6

Figure 2 shows the cesium conduction data obtained from prototype T-205, compared with that from prototypes T-203B and T-204. The data for T-205 was plotted assuming that the effective heat transfer area would equal 3.50 sq cm. As can be seen, it tends to indicate that the interelectrode spacing of Converter T-205 was of the order of 2.60 mils,

* The collector temperature of these runs was too high (1.75 times the reservoir temperature instead of 1.60).

as compared with the design value of 4.20 mils. The reason for the difference between the measured and calculated values of spacing is probably the fact that the effective area for cesium heat transfer may be appreciably greater than 3.50 sq cm. In fact, the value of 3.50 sq cm is based on the planar area of 2.50 sq cm and the collector lateral area of 1 sq cm, which in Converter T-205 was spaced 4 mils from the emitter support sleeve. Therefore, it seems likely that the interelectrode spacing of Converter T-205 was greater than 2.60 mils, and somewhere between 2.60 and 4.20 mils.

During the fourth quarter it was found that recent data for the thermal conductivity of rhenium indicates that the conductivity is substantially higher than previously assumed.* Consequently, the calculation of the temperature drop between the hohlraum and the emitter surface of the converter has been recalculated as follows. For the solid rhenium emitter, the distance from the hohlraum to the emitter face is approximately 0.045 in. or 0.114 cm. The converter heat transfer has been calculated to be approximately (34.6 + 1.09 I) watts/cm^2 in the vicinity of 2000°K emitter temperature. Assuming the thermal conductivity of rhenium to be 0.48 watt/cm - °K at 2000°K, the calculated emitter temperature drop for a solid rhenium emitter is

$$\Delta T = 10 + 0.25\ I, \quad {}^\circ C$$

where I is the output current of the converter in amperes. The above expression gives just about the value previously observed in pressure-bonded structures of tantalum and rhenium.

* "Thermal Conductivity of Ta, W, Re, Ta-10W, T-111, T-222, W-25 Re in the Temperature Range 1500°K-2800°K," by C.K. Gun and M. Hoch, University of Cincinnati, Cincinnati, Ohio.

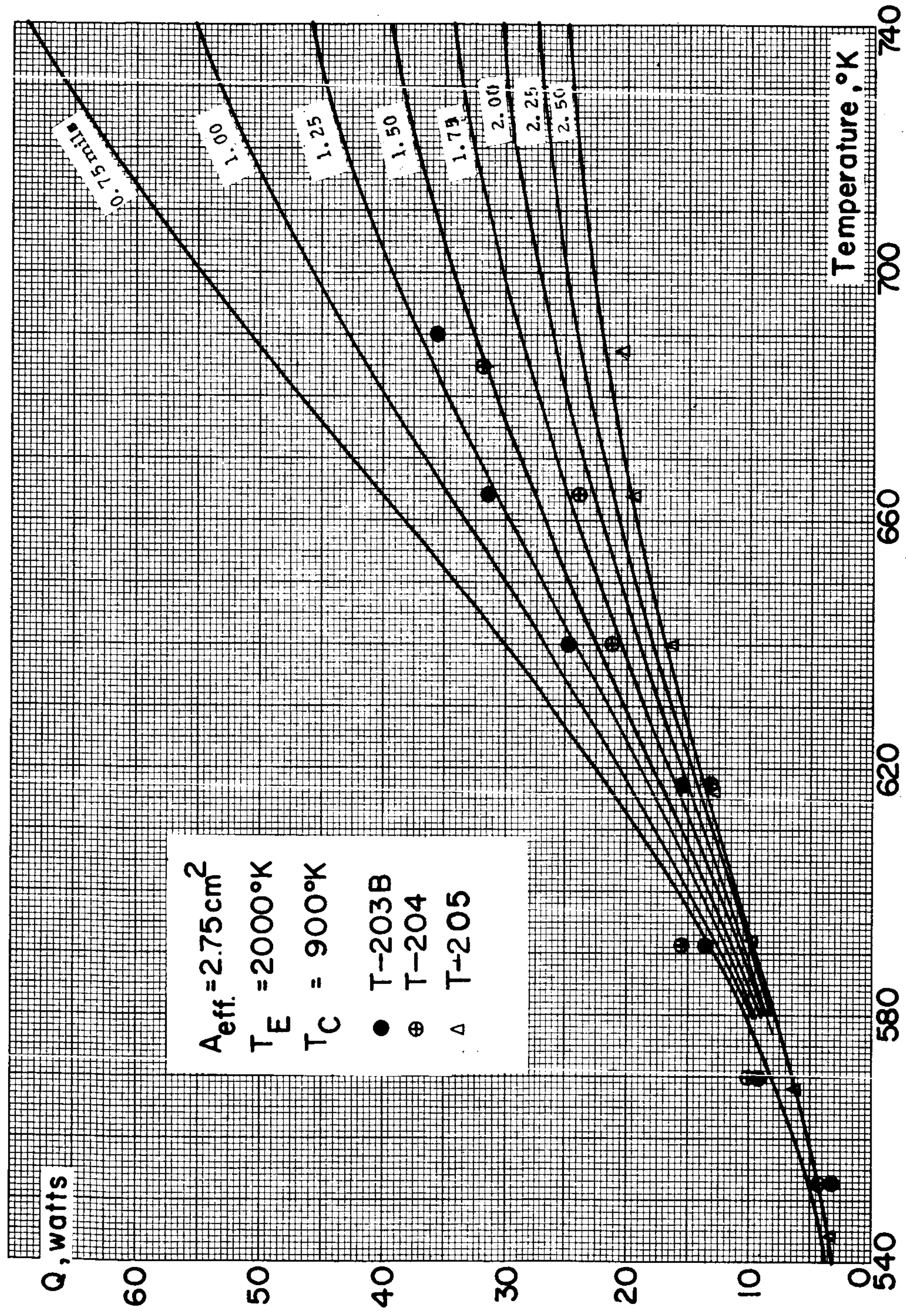

Q, watts
Temperature, °K
0.75 mils
1.00
1.25
1.50
1.75
2.00
2.25
2.50
A eff. = 2.75 cm²
T E = 2000°K
T C = 900°K
● T-203B
⊕ T-204
△ T-205
0
10
20
30
40
50
60
540
580
620
660
700
740

Figure 2

1.4 Emissivity Measurement of Radiator Coatings

As explained in the Third Quarterly Report, a program has been conducted to evaluate the emissivity of various coating materials. The materials reported in the Third Quarterly were chromium carbide, zirconium carbide and chromium oxide. The measured values of thermal emissivity for these coatings were, respectively, 0.61, 0.61, and 0.98. During the reporting period, two additional materials, aluminum oxide (Rockide A) and zirconium oxide, have been evaluated using the same experimental procedures. Both of these materials were found to have relatively poor emissivity. The value measured for Rockide A was 0.70 and that for zirconium oxide 0.59. The results obtained on the five materials tested indicate that, from an emissivity standpoint, chromium oxide has far superior qualities. The decision to explore other materials than chromium oxide had resulted from the observation that, under certain circumstances, chromium oxide coatings may have defective adherence to the substrate to which they are applied. In view of the difficulty in finding any material with an emissivity as high as that of chromium oxide, regardless of its mechanical adherence properties, it is felt that improvements in radiator coatings will best be obtained by focusing attention on the methods of application of chromium oxide coatings rather than by the exploration of any new coating material. Therefore, no additional materials for radiator coatings will be evaluated under this program, and only minor investigations of the method of application of chromium oxide coatings are planned.

1.5 Fabrication of Rhenium Tubing

The supplier of rhenium tubing, the rhenium division of the Chase Brass Company, has relocated from Waterbury, Connecticut, to Solon, Ohio. As a result of this relocation the Chase Brass Company was no longer in a position to fabricate rhenium tubing to custom dimensions. Since an insufficient amount of rhenium tubing was on hand to fabricate the last four prototypes under this program, in-house fabrication of rhenium tubing was pursued very actively. Furthermore, it was discovered during the fourth quarter that the available rhenium tubing was often of marginal quality and in a few instances developed leaks in the region of the seam weld. Figure 3 shows one such sleeve, where it may be observed that the arc-welded seam is not uniformly melted on both sides of the seam. The material on only one side has been melted, and then it has resolidified against the unmelted abutting edge at the seam. Although the resulting weld is leak-tight, work under other programs at Thermo Electron has shown that the weld can fail after a few thermal cycles to normal operating conditions.

The in-house effort to fabricate rhenium tubing has consisted of ordering flat rhenium stock 0.020" thick, cutting it to the necessary dimensions, rolling it and electron-beam welding it. Both the rolling and electron-beam welding operations have been performed by outside vendors. Figure 4 shows the three sizes of rhenium tubes required for prototype fabrication after the beam-welding operation. In the following quarter, the tubes will be ground to final dimensions.

1.6 Fabrication of Pressure-Bonded Palladium Collector

Because of the likelihood that one of the collector materials to be evaluated in the remainder of the program is palladium, and because of the complete lack of knowledge on the technology of bonding palladium to appropriate substrate materials, a component evaluation effort of small magnitude was conducted. This effort consisted of preparing two subassemblies of parts for pressure-bonding palladium to a piece of molybdenum of a size suitable for being machined into collector structures for any of the subsequent prototypes. When an attempt was made, by electron-beam welding, to seal the tantalum container which would serve as the pressure-bonding envelope, the temperature reached by the tantalum in the immediate vicinity of the palladium piece was sufficient to cause melting of the latter. This container was cut open, and is shown in Figure 5. The second container was modified so that the thickness of the tantalum wall conducting heat to the palladium piece was reduced, and it could be successfully welded. It has now been pressure-bonded, and, although not yet finally machined, it seems to be satisfactory for use.

1.7 Fabrication of Pressure-Bonded Rhenium Collector

The fabrication of a pressure-bonded rhenium collector was investigated to determine whether the bonded rhenium face on the collector would withstand all the machining operations and the high-temperature firing required in preliminary processing. Both the molybdenum and the rhenium pieces were cleaned and fired prior to pressure-bonding; the assembled structure has now been machined, and the collector face has been lapped. Next, it will be degreased, ultrasonically cleaned, and fired at 1350 to 1400°C in vacuum for 1/2 hour. The part as machined is shown in Figure 6.

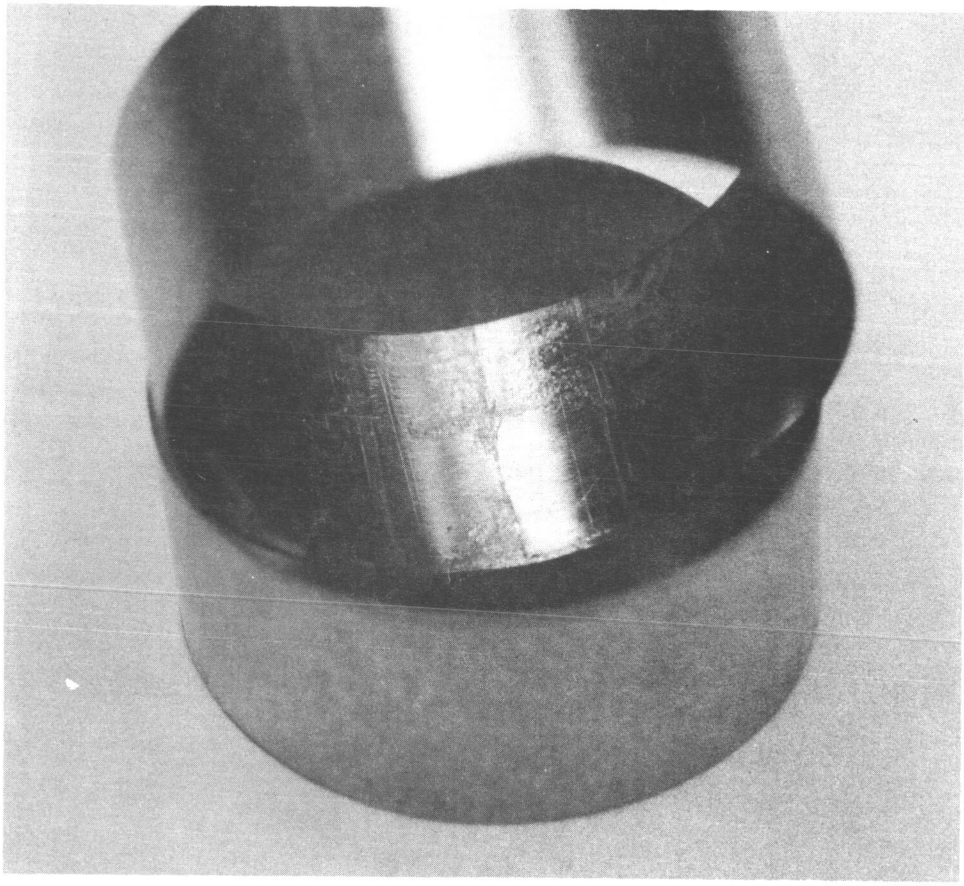


Figure 3

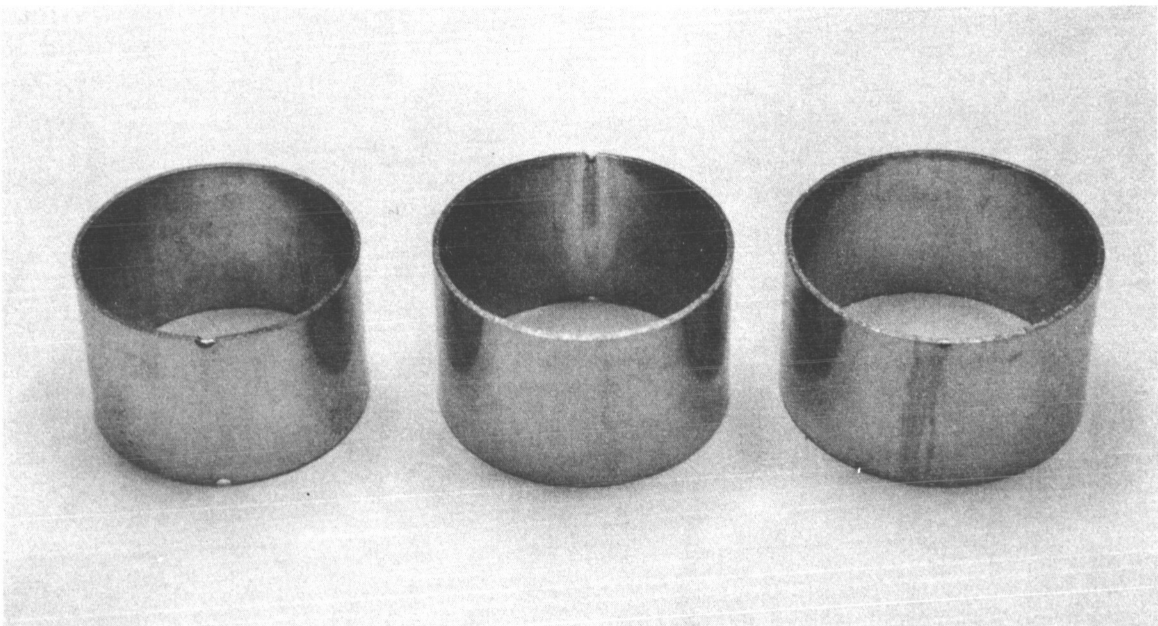


Figure 4

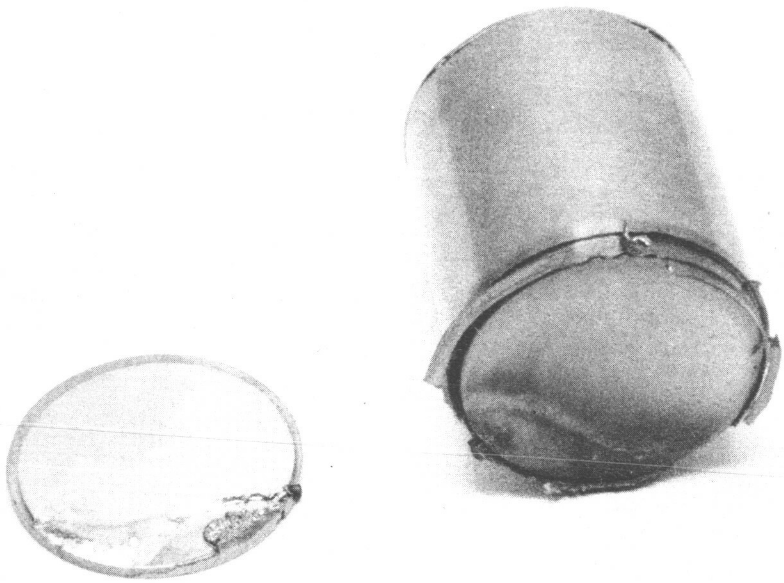


Figure 5

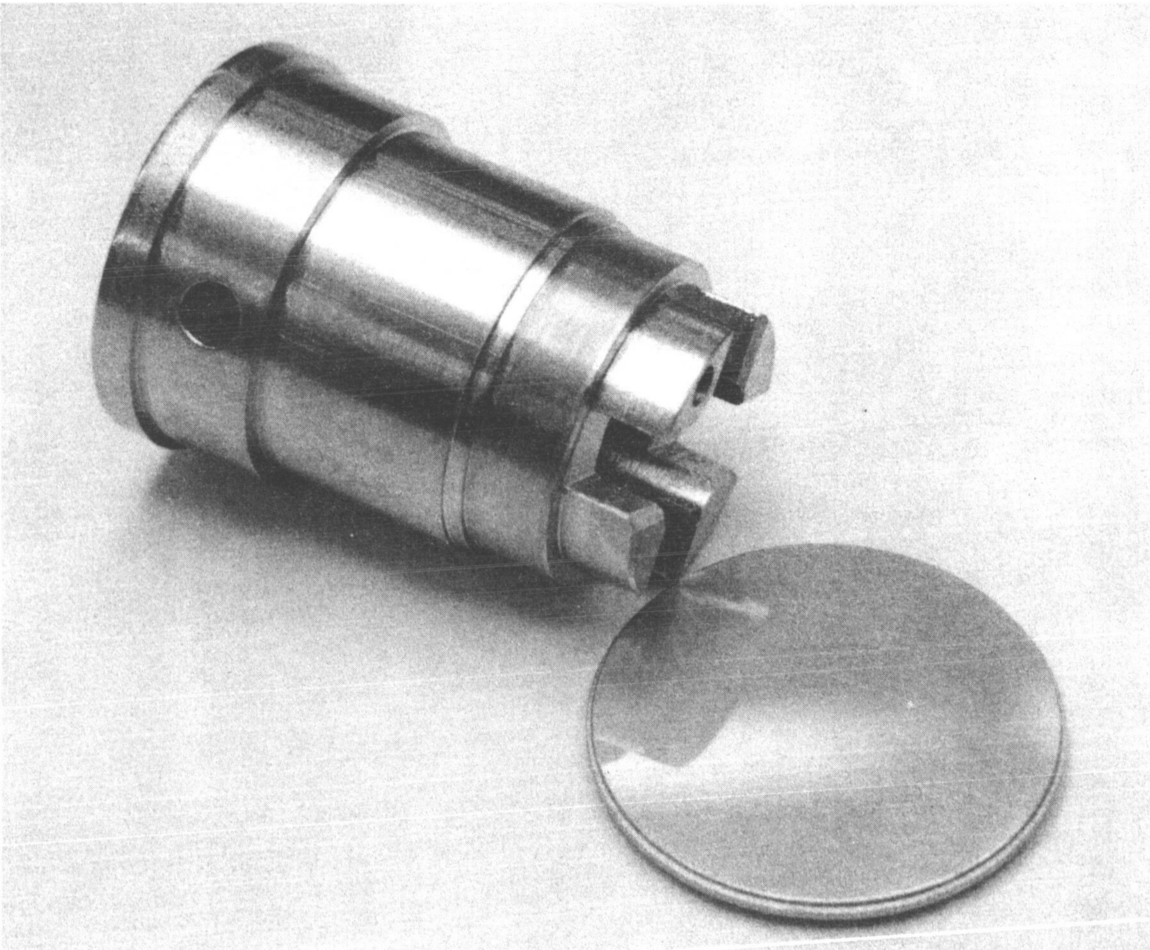


Figure 6

1.8 Lapping of Rhenium Emitters

In order to improve on the flatness of the emitters used, a lapping procedure has been investigated for use prior to electroetching. The emitters are machined out of annealed 0.060" flat stock, and then lapped on an aluminum oxide flat with four grades of diamond lapping compounds. To evaluate the procedure, the surface flatness of the emitters will be checked after electroetching and thermal stabilization. Figure 6 also shows a lapped emitter, where it can be seen that the finish on the lapped face is of near optical quality.

CHAPTER 2

2.1 Preliminary Analysis of Generator Performance

Figure 7 is a reproduction of Figure 31 of the First Quarterly Report, where the net heat available per converter for each of the two families of homologous converters in the generator is given as a function of cavity aperture diameter and the number of converters in the generator. The converters identified by the nomenclature QC3 are those which lie closest to the cavity aperture, and those labeled QC4 are those near the bottom of the cavity. The calculation was performed for the case of ground test with an 11.5-ft-diameter mirror at a solar radiation of 90 watts per sq ft. Other assumptions were that the converters lying close to the cavity aperture would have a cavity surface thermal emissivity of 0.25 and the others 0.365, to ensure thermal balance. It was also assumed that the mirror would have a reflectivity of 88%, a shadow loss of 5%, and a window loss of 11%, and that it would deliver flux in the amount shown in Figure 8. The procedure used to calculate the curve in Figure 8 is also presented in the First Quarterly Report, and it is just a direct geometrical scale-up of the performance of the best electroformed 5-ft-diameter concentrators known.

Experience with the 5-ft-diameter concentrators has shown that, although these concentrators have an optimum cavity aperture of 0.5 inch, the aperture often has to be enlarged by as much as 40% in order to obtain optimum performance in actual solar tests of thermionic generators. As Figure 7 indicates, there is a maximum possible cavity aperture for each generator design, which is governed by the average cavity diameter, and this in turn is a function of the number of converters clustered around the generator cavity. For design purposes it should be assumed that the maximum practical cavity apertures corresponding to generators having 10, 12, 14, and 16 converters are 1.0, 1.25, 1.50 and 1.75 inches. To the 0.5-inch optimum cavity aperture diameter for a 5-ft diameter concentrator there corresponds a 1.15-inch optimum aperture for an 11.5-ft diameter concentrator. If this latter cavity aperture value is in turn increased by 40%, it is found that a cavity aperture diameter of 1.61 inches might be desirable. This figure could be still larger if the geometrical accuracy of the 11.5-ft-diameter concentrator is substantially worse than that of the 5-ft concentrator. Thus it appears that only 14-converter and 16-converter generators are large enough to operate with an 11.5-ft concentrator diameter, and that the 14-converter generator size is marginally satisfactory.

In the following analysis the electrical performance of the generator is calculated on the basis of preliminary reference converter data which is given in Figure 9. This data is the average performance observed in production-type converters, scaled up by the ratio of emitter areas of the present T-200 converters to that of the production converters, namely 2.587/2.076 = 1.246. For a hohlraum temperature of 2000°K the scaled-up data is as follows:

V = 0.6 Volt	I = 84.3 Amperes
= 0.8 Volt	= 52.3 Amperes
= 1.0 Volt	= 21.6 Amperes
= 1.2 Volts	= 14.3 Amperes

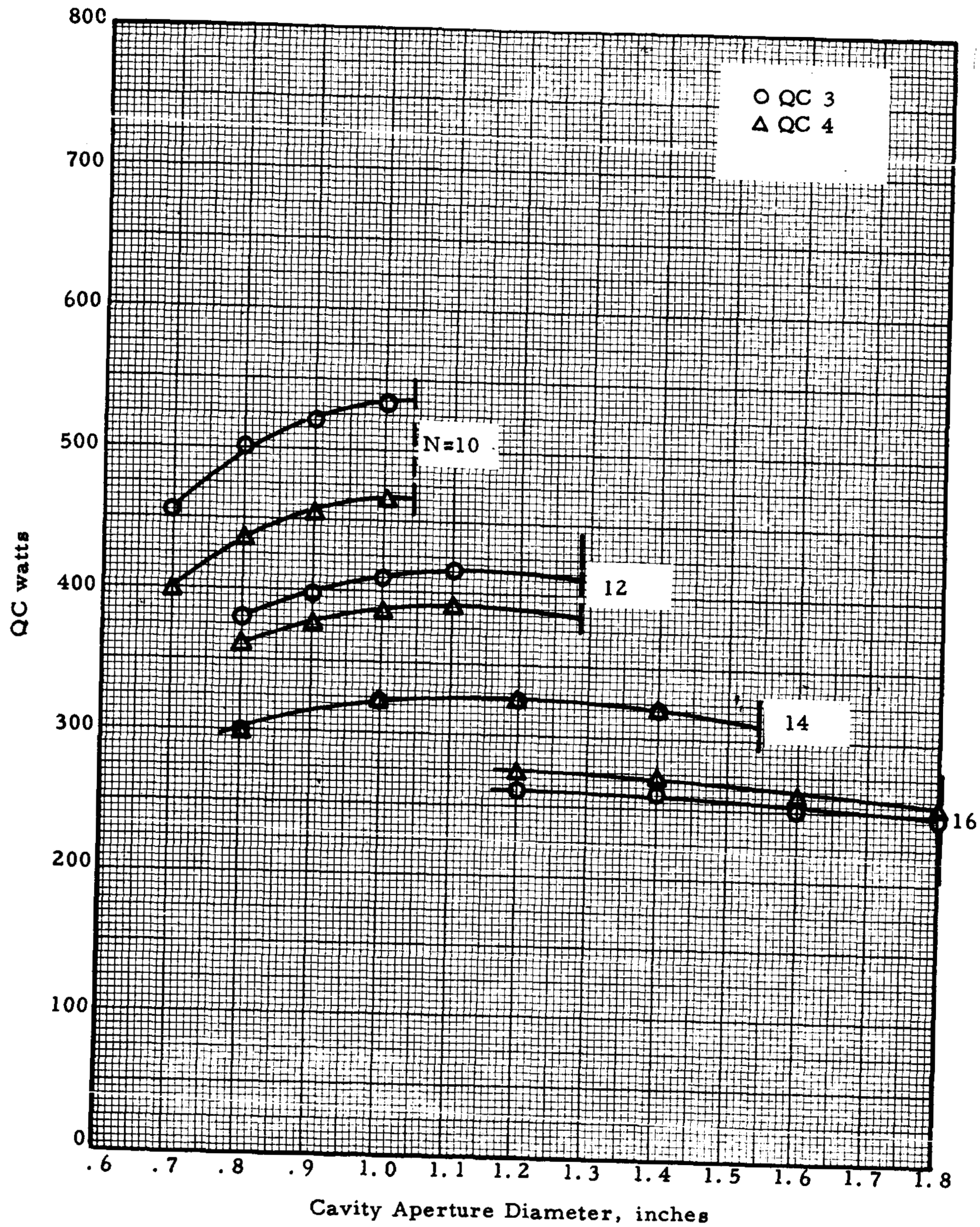

800
700
600
500
400
300
200
100
0
QC watts
○ QC 3
△ QC 4
N=10
12
14
16
.6
.7
.8
.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
Cavity Aperture Diameter, inches

Figure 7

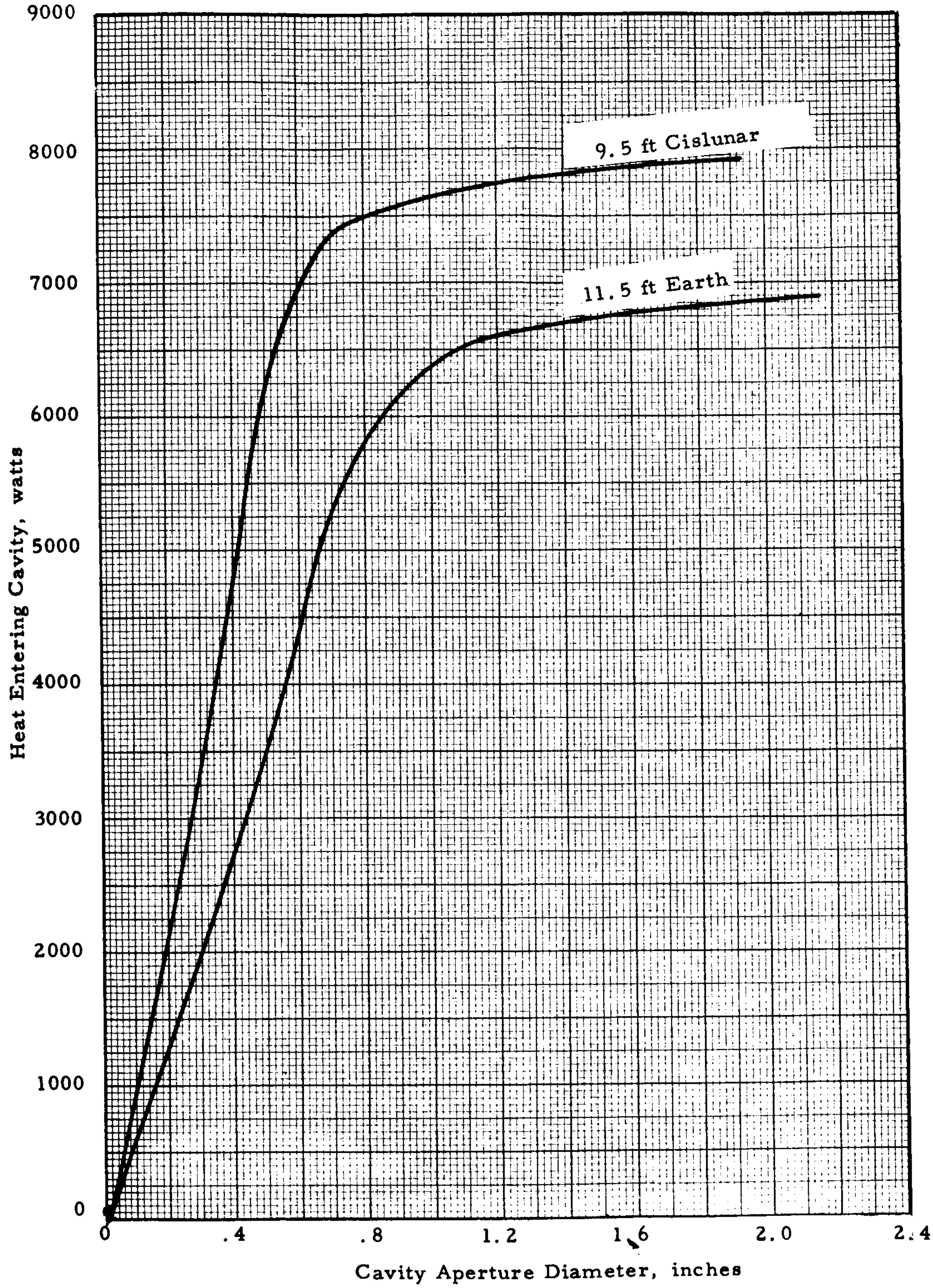

9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Heat Entering Cavity, watts
9.5 ft Cislunar
11.5 ft Earth
0
.4
.8
1.2
1.6
2.0
2.4
Cavity Aperture Diameter, inches

Figure 8

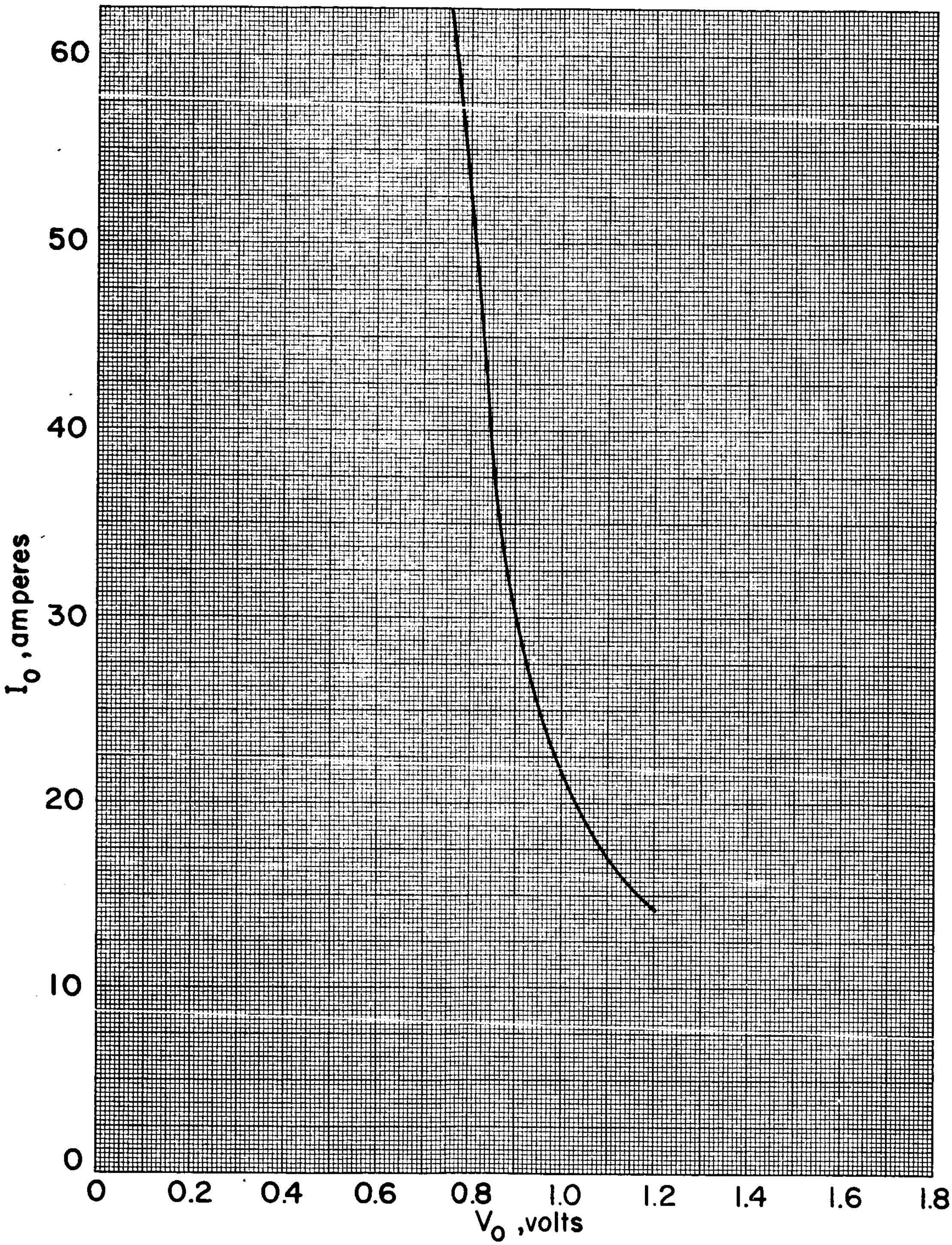


Figure 9

The assumed cavity apertures are 1.50 inches for the 14-converter generator and 1.75 inches for the 16-converter generator. With these assumptions, Figure 7 shows that the corresponding average values of net heat received by the converters are 315 watts and 250 watts. Since an 11.5-ft-diameter mirror is not likely to achieve the same degree of optical accuracy as the best 5-ft concentrators, the net heat received by the converters should be reduced in proportion to the smallness of the required image at the focal point. In this calculation the value of 315 watts for the 14-converter generator has been reduced by 10% to 283 watts, and that for the 16-converter generator by 5% to yield a net heat value of 237 watts.

Knowing the amount of net heat available to the converters, it is then possible to calculate the output current that the converters will be capable of delivering at 2000°K. To do this, the converter heat losses are estimated as follows:

The cesium conduction is given by Figure 2. Assuming a reservoir temperature of 350°C and an interelectrode spacing of 2 mils, the total value is 16 watts.

The emitter support conduction loss was calculated and given in Table 7, page 105, of the Task II Final Report, Contract 950671, and is 58 watts total.

The interelectrode radiation calculated for an emitter and collector emissivity of 0.28, assuming an emitter temperature of 2000°K and a collector temperature of 1040°K, is 34.4 watts.

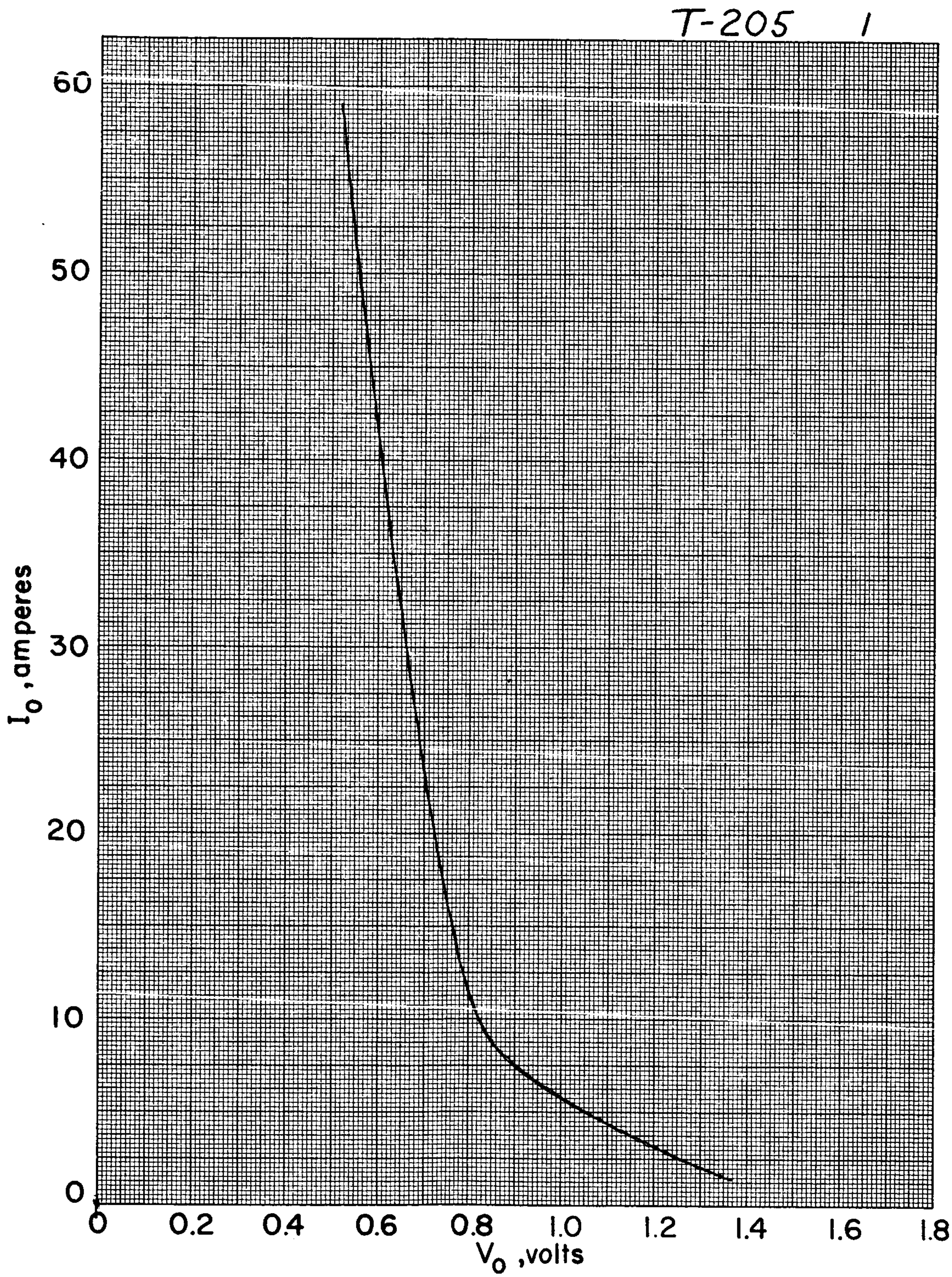
Other radiation losses are the internal radiation from the portion of the emitter surface which is not opposite the collector surface, and the external radiation from the lateral area of the emitter. The internal annular radiating area has a diameter of 0.706 inch and a width of 6 mils, and its value is 0.0865 sq cm. The corresponding internal radiation loss, assuming an emissivity of 0.28 and radiation between the temperatures of 2000°K and 1040°K, is then 2.05 watts. To calculate the external lateral radiation from the emitter, it is assumed that the radiating surface is 0.040 inch high on a diameter of 0.727 inch, yielding a value of 0.581 sq cm area. Again assuming an emissivity of 0.28, conservatively assuming that the shielding around the emitter will reduce the heat losses by only 15% (that is, a shielding factor of 0.85), and assuming radiation between the temperatures of 2000°K and 1040°K, the heat loss calculated is 11.65 watts. The total of the additional radiation losses is therefore 13.7 watts.

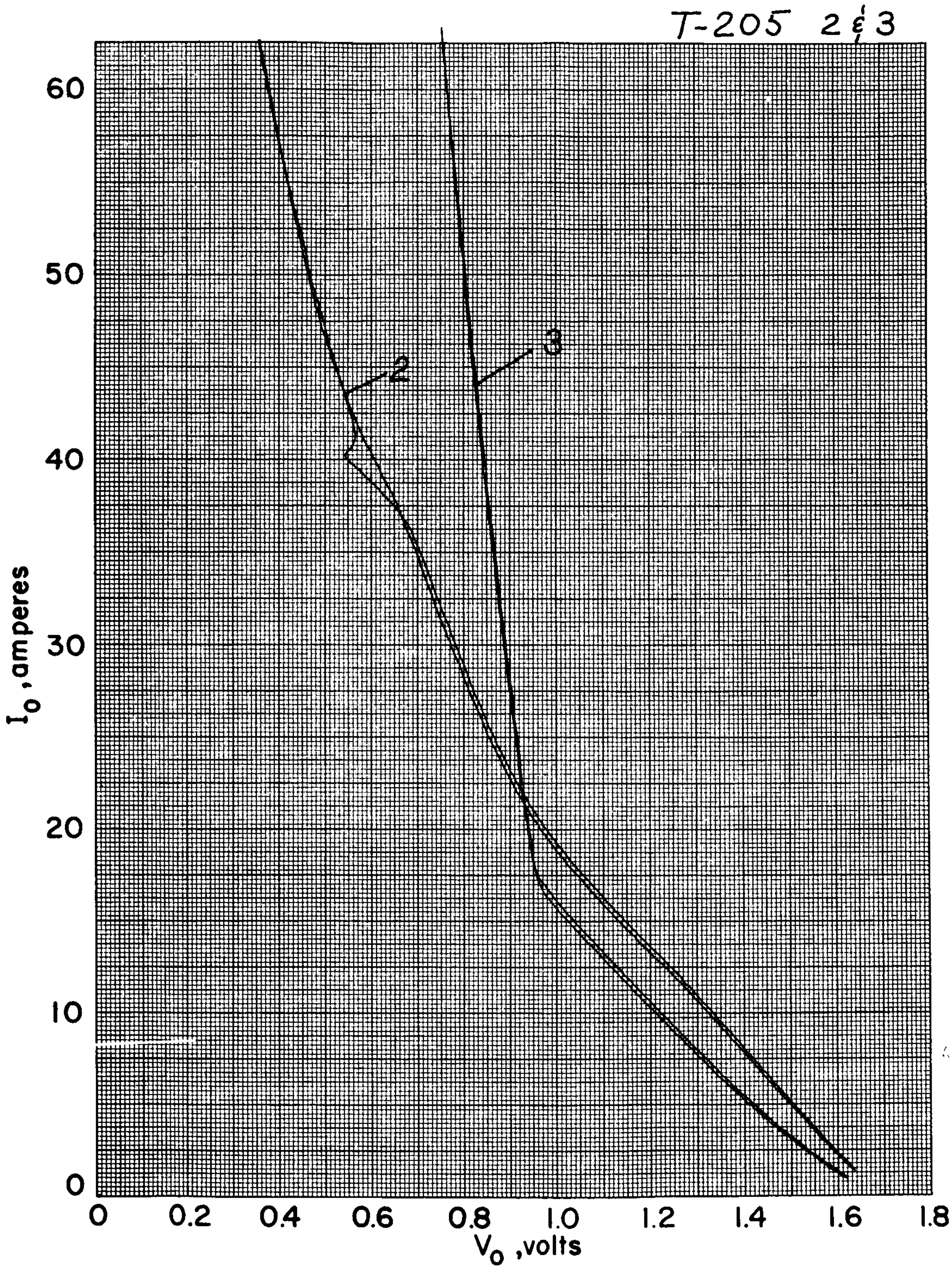
Adding all these heat losses, it is found that the fixed losses per converter amount to 122.1 watts. The total heat required per converter is the sum of the fixed losses and the electron-cooling heat loss. In the work done under Contract 950671, Task II, it was found that electron cooling heat loss is nearly constant and is equal to 2.72 watts per ampere of output. A preliminary analysis of the T-204 data indicates that the electron-cooling loss is about 2.78 watts per ampere. Assuming this more conservative value, it is then found that the converter heat losses will equal the net available heat quantities of 283 and 237 watts when the output current is 58 amperes (for the 14-converter generator) and 41.5 amperes (for the 16-converter generator).

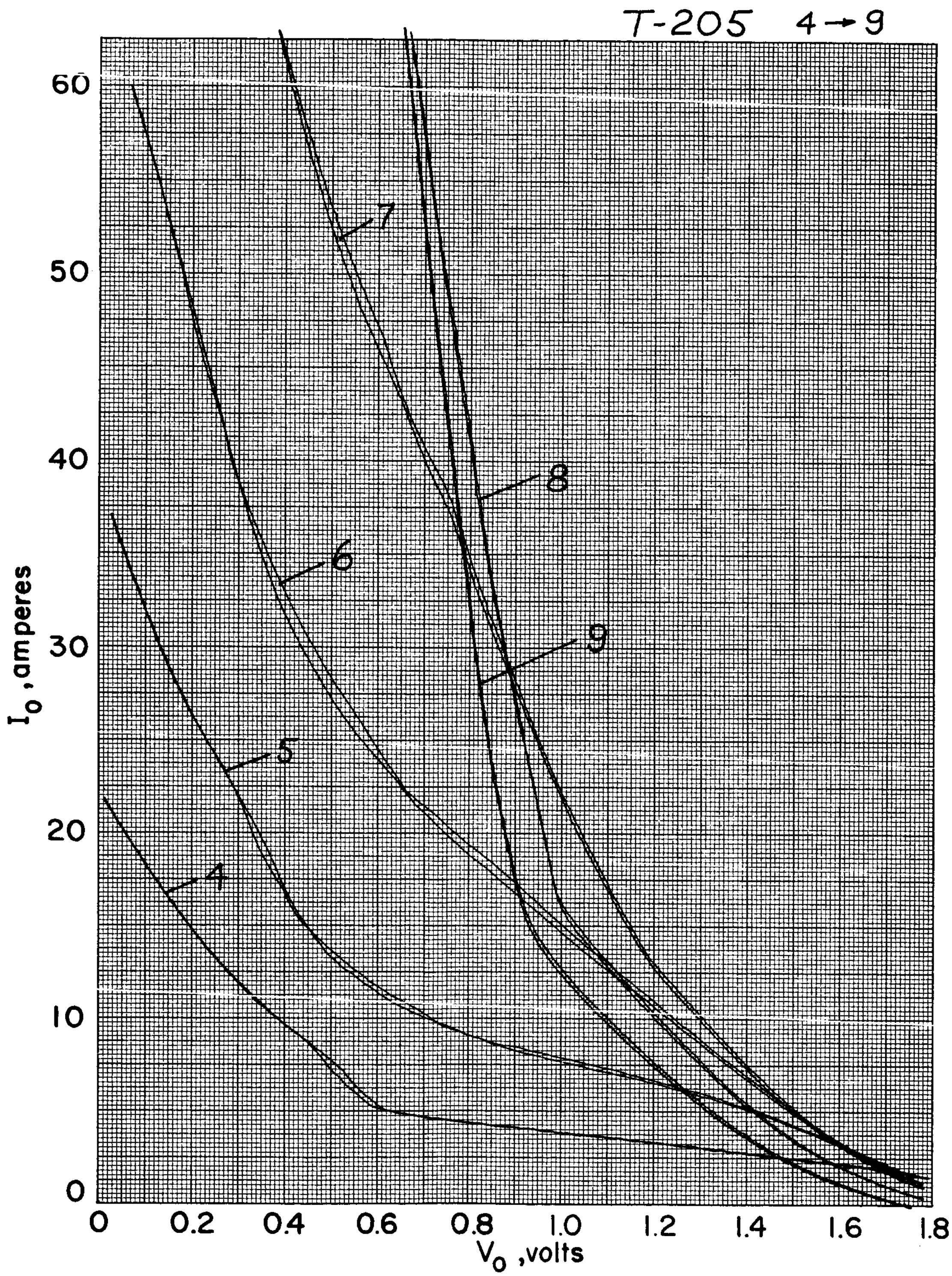
The reference data plotted in Figure 9 shows that these output current values will be obtained at corresponding output voltages of 0.77 volt and 0.84 volt. Thus, each converter of the 14-converter generator will have an output power of 44.5 watts, and for the 16-converter generator this will be 34.8 watts. A summary of the performance characteristics for the two designs is presented below:

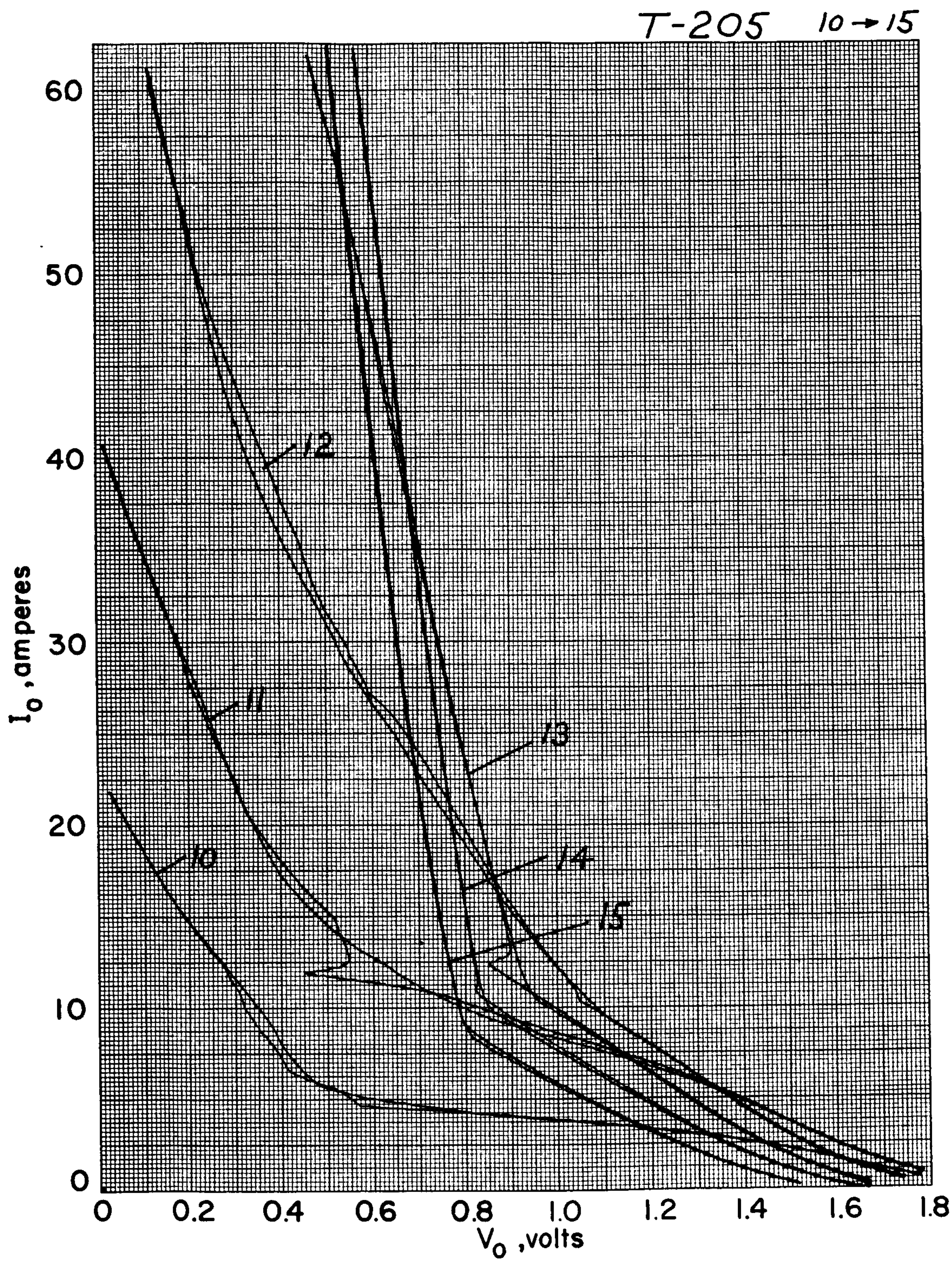
	N=14	N=16
Cavity aperture, in.	1.50	1.75
Nominal heat received, watts	6750	6810
Corrected heat input (10%, 5%) watts	6070	6480
Converter output current, amperes	58	41.5
Converter output voltage, volts	0.77	0.84
Converter output power, watts	44.5	34.8
Generator output power, watts	623	557
Aperture area, cm^2	11.4	15.5
Black body reradiation from cavity, watts	1040	1410
Net Heat received by generator, watts	5030	5070
Generator efficiency, %	12.4	11.0

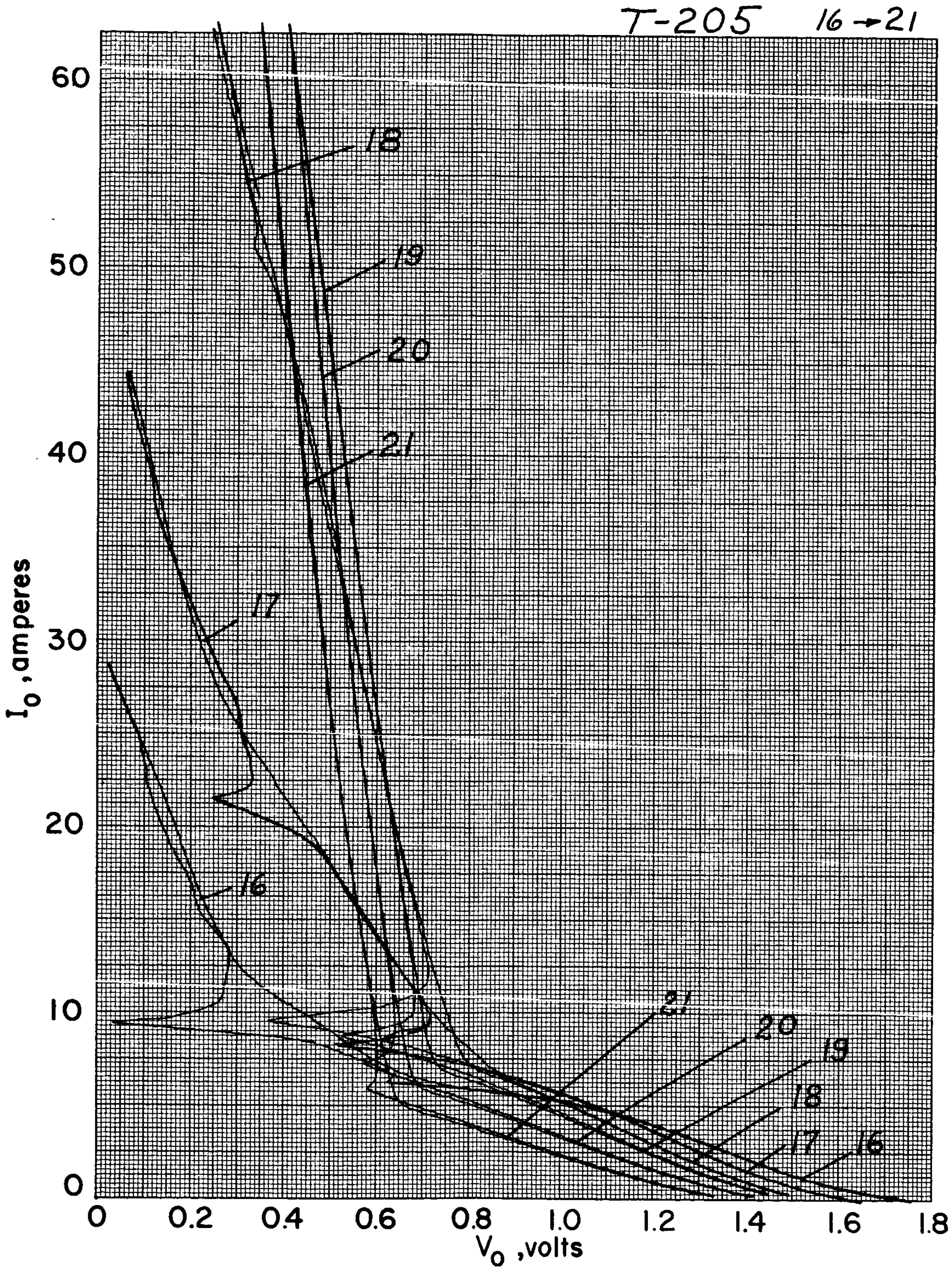
It can be seen that the 14-converter design produces more overall power, but this is based on the assumption that a sufficiently accurate concentrator will be available, and also on the assumption that the I-V characteristic of the converters used will be as steep as that shown in Figure 9. The data obtained so far in this program indicates that the I-V characteristic will be less steep; that is, the output at the higher voltages will be larger, or at the lower voltages it will be smaller, thus tending to reduce the magnitude of the difference in converter output power that is predicted in the above table. Based on the above, it seems clearly preferable to proceed with the design of a multi-converter generator which would use 16 converters, the largest number of converters considered.


T-205 1
I_o, amperes
0
10
20
30
40
50
60
V_o, volts
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8

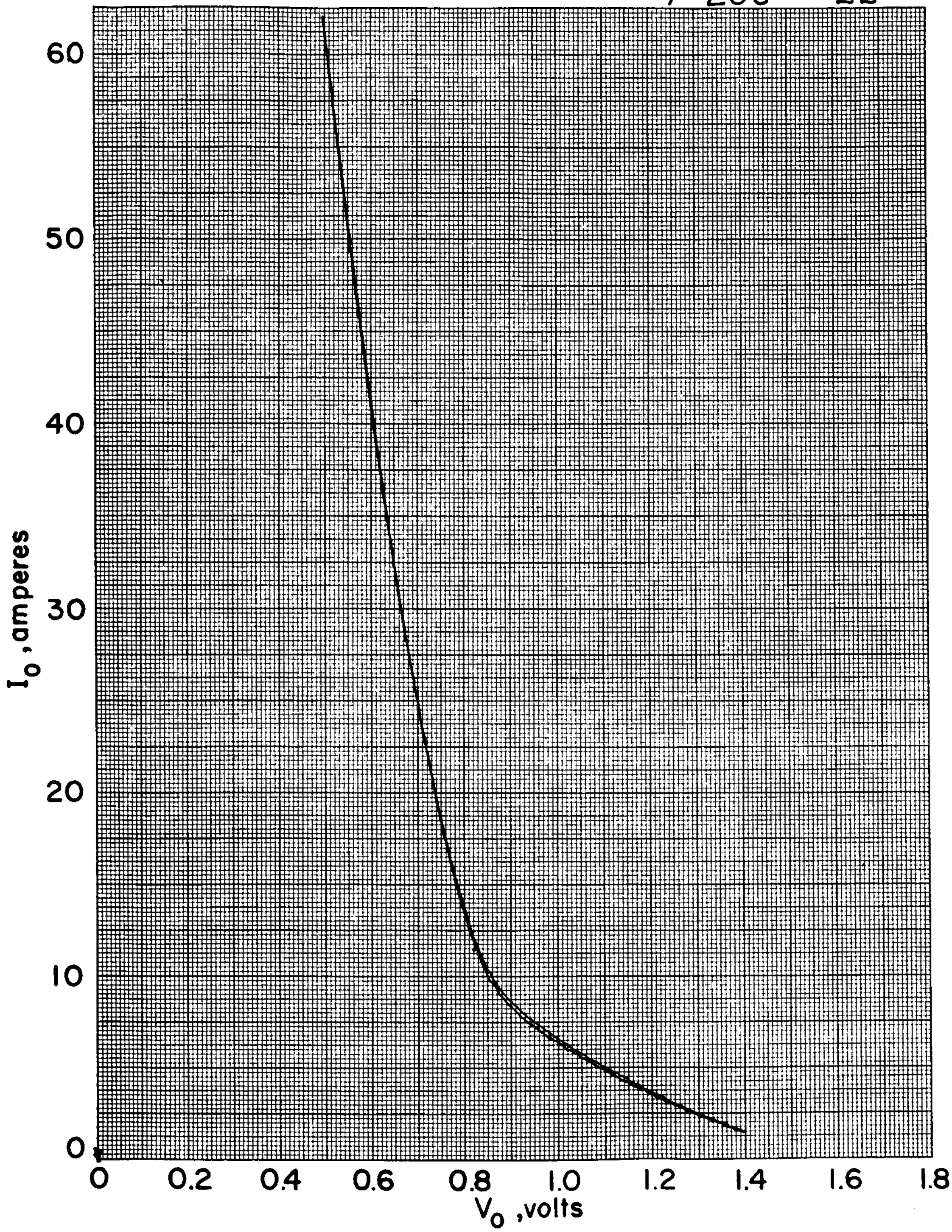

T-205 2 & 3
60
50
40
30
20
10
0
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
I_o, amperes
V_o, volts
2
3


T-205 4→9
60
50
40
30
20
10
0
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
I_o, amperes
V_o, volts
4
5
6
7
8
9


T-205 10 → 15
60
50
40
30
20
10
0
I_o, amperes
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
V_o, volts
10
11
12
13
14
15


T-205 16→21
18
19
20
21
17
16
21
20
19
18
17
16
60
50
40
30
20
10
0
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
I_0, amperes
V_0, volts

T-205 22



THERMO ELECTRON
ENGINEERING CORPORATION

Sheet 1 of 6

Converter No. T-205 Run No. 1 & 2 Observer P. [illegible]

VARIABLE		1	2	3	4	5	6	7	8	9	10
Date		10-17	10-17	10-17	10-17	10-17	10-17	10-18	10-18	10-19	
Time		11:18	11:45	13:33	13:46	14:30	17:24	14:55	17:13	10:18	
Elapsed Time, Hours		0	0.4	2.2	2.4	3.1	6.1	9.8	12.1	29.2	
T_O, °C		1731	1710	1738	1738	1738	1740	1740	1750	1752	
T_O Corrected, °C		1741	1724	1748	1748	1748	1750	1750	1760	1762	
$\Delta T_{Bell\ Jar}$, °C		14	14	14	14	14	14	14	14	14	
T_H, °C		1755	1738	1762	1762	1762	1764	1764	1774	1776	
ΔT_E, °C		35	31	35	35	35	35	45	45	44	
T_E, °K		1993	1980	2000	2000	2000	2002	1992	2002	2005	
V_O, volts		.898	—	—	—	.920	.902	.772	.759	.716	
I_O, amps		29.2	27	30	30	30.9	30.9	49.3	49.0	47.5	
P_O, watts		—	—	—	—	29.4	—				
I-V Trace No.		—	1	2	3	—	—	—	—	—	
T_R	mv	12.2	16.7	11.8	14.3	13.1	12.9	13.9	13.9	13.9	
	°C	300	407	290	350	321	317	341	341	341	
	°K	573	680	563	623	594	590	614	614	614	
T_C	mv	—	—	—	—	—	—	—	—	—	
	°C	730	769	732	745	745	745	770	770	765	
	°K	1003	1042	1005	1018	1018	1018	1043	1043	1038	
T_C base inner	mv						SHUT OFF				
	°C						(1)			(2)	
T_C base outer	mv										
	°C										
$T_{Radiator}$	mv	21.3	22.6	21.6	21.6	21.6	21.6	20.1	20.0	20.1	
	°C	516	546	522	522	522	522	487	485	487	
V_{eb}, volts		973	972	970	970	968	968	961	961	962	
I_{eb}, mA		302	297	296	312	320	320	377	377	377	
$E_{Filament}$, volts		5.2	5.2	5	5	5	5	5.2	5.2	5.2	
$I_{Filament}$, amps		18	18	17.5	17.5	17	17	18	18	18	
$I_{Coll.\ Heater}$, amps		0	4	0	0	0	0	0	0	0	
$I_{Res.\ Heater}$, amps		0	1	0	1	1	1	1	1	1	
Vacuum, 10^{-6} mm Hg		12	10	4	4	3.6	3.0	4	3.6	2.8	
Measured Efficiency, %		—	—	—	—	9.4	—	—	—	—	

NOTES: (1) SHUT OFF TO ADD COLLECTOR COOLING. ADDED COLD STRAP + 4 ADDITIONAL FINS (ZrO_2).

(2) SHUT OFF TO CLEAN BELLJAR.

THERMO ELECTRON
ENGINEERING CORPORATION

Sheet 2 of 6

Converter No. T-205 Run No. 3 Observer P. Brosur

VARIABLE		1	2	3	4	5	6	7	8	9	10
Date		10-19	10-19	10-19	10-19	10-19	10-19	10-19	10-20	10-20	10-20
Time		14:28	14:35	14:50	15:05	15:15	15:25	15:58	9:05	9:36	10:56
Elapsed Time, Hours		31.0	31.2	31.4	31.7	31.8	32.0	32.5	49.7	50.2	50.5
T_O, °C		1732	1731	1739	1741	1739	1739	1630	1635	1639	1639
T_O Corrected, °C		1742	1741	1749	1751	1749	1749	1639	1645	1649	1649
$\Delta T_{Bell\ Jar}$, °C		14	14	14	14	14	14	12	12	12	12
T_H, °C		1756	1755	1763	1765	1763	1763	1651	1657	1661	1661
ΔT_E, °C		25	28	34	35	34	34	24	30	34	34
T_E, °K		2004	2000	2002	2003	2002	2002	1900	1900	1900	1900
V_O, volts											
I_O, amps		$\overline{10}$	$\overline{16}$	$\overline{28}$	$\overline{30}$	$\overline{28}$	$\overline{28}$	$\overline{8}$	$\overline{20}$	$\overline{28}$	$\overline{28}$
P_O, watts											
I-V Trace No.		4	5	6	7	8	9	10	11	12	13
T_R	mv	11.0	11.8	12.6	13.4	14.3	15.2	11.0	11.8	12.6	13.4
	°C	271	290	310	329	350	372	271	290	310	329
	°K	544	563	583	602	623	645	544	563	583	602
T_C	mv										
	°C	597	627	660	700	724	759	597	627	660	700
	°K	870	900	933	973	997	1032	870	900	933	973
T_C base inner	mv										
	°C										
T_C base outer	mv										
	°C										
$T_{Radiator}$	mv										
	°C										
V_{eb}, volts		—	—	—	—	—	—	—	—	—	—
I_{eb}, mA		—	—	—	—	—	—	—	—	—	—
$E_{Filament}$, volts		—	—	—	—	—	—	—	—	—	—
$I_{Filament}$, amps		—	—	—	—	—	—	—	—	—	—
$I_{Coll.\ Heater}$, amps		—	—	—	—	—	—	—	—	—	—
$I_{Res.\ Heater}$, amps		—	—	—	—	—	—	—	—	—	—
Vacuum, 10^{-6} mm Hg		3.2	3.2	3.2	3.1	3.1	3.1	2.7	2.2	2.2	2.2
Measured Efficiency, %											

NOTES:

THERMO ELECTRON
ENGINEERING CORPORATION

Sheet 3 of 6

Converter No. T-205 Run No. 3 & 4 Observer P. Brosen

VARIABLE		1	2	3	4	5	6	7	8	9	10
Date		10-20	10-20	10-20	10-20	10-20	10-20	10-20	10-20	10-20	
Time		10:11	10:19	13:00	13:12	13:21	13:28	14:10	14:40	15:00	
Elapsed Time, Hours		50.8	50.9	53.6	53.8	54.0	54.1	54.9	55.3	55.6	
T_O, °C		1638	1638	1534	1538	1541	1543	1542	1542	1710	
T_O Corrected, °C		1648	1648	1542	1546	1549	1551	1550	1550	1724	
$\Delta T_{Bell\ Jar}$, °C		12	12	10	10	10	10	10	10	14	
T_H, °C		1660	1660	1552	1556	1559	1561	1560	1560	1738	
ΔT_E, °C		33	33	25	29	32	34	33	33	31	
T_E, °K		1900	1900	1800	1800	1800	1900	1800	1800	1980	
V_o, volts											
I_o, amps		$\overline{26}$	$\overline{27}$	$\overline{10}$	$\overline{18}$	$\overline{24}$	$\overline{28}$	$\overline{26}$	$\overline{26}$	$\overline{27}$	
P_o, watts											
I-V Trace No.		14	15	16	17	18	19	20	21	22	
T_R	mv	14.3	15.2	11.0	11.8	12.6	13.4	14.3	15.2	16.7	
	°C	350	372	271	290	310	329	350	372	407	
	°K	623	645	544	563	583	602	623	645	680	
T_C	mv										
	°C	724	759	597	627	660	700	724	759	769	
	°K	997	1032	870	900	933	973	997	1032	1042	
T_C base inner	mv										
	°C										
T_C base outer	mv										
	°C										
$T_{Radiator}$	mv									21.7	
	°C									525	
V_{eb}, volts										971	
I_{eb}, mA										315	
$E_{Filament}$, volts										5	
$I_{Filament}$, amps										17	
$I_{Coll.\ Heater}$, amps										9	
$I_{Res.\ Heater}$, amps										1	
Vacuum, 10^{-6} mm Hg		2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	
Measured Efficiency, %											

NOTES:

THERMO ELECTRON
ENGINEERING CORPORATION

Sheet 4 of 6

Converter No. T-205 Run No. 5 Observer P. Brosens

VARIABLE		1	2	3	4	5	6	7	8	9	10
Date		10-20	10-20	10-20	10-20	10-20	10-20	10-20			
Time		15:35									
Elapsed Time, Hours		56.2									
T_O, °C		1723									
T_O Corrected, °C		1733									
$\Delta T_{Bell\ Jar}$, °C		14									
T_H, °C		1747									
ΔT_E, °C		20									
T_E, °K		2000									
V_O, volts											
I_O, amps		0	0	0	0	0	0	0			
P_O, watts											
I-V Trace No.											
T_R	mv	11.0	12.0	13.0	14.0	15.0	16.0	17.0			
	°C	271	295	319	343	367	391	414			
	°K	544	568	592	616	640	664	687			
T_C	mv										
	°C	627	627	627	627	627	627	627			
	°K	900	900	900	900	900	900	900			
T_C base inner	mv										
	°C										
T_C base outer	mv										
	°C										
$T_{Radiator}$	mv										
	°C										
V_{eb}, volts		987	987	986.4	985.6	985.2	984.9	984.4			
I_{eb}, mA		213.0	217.1	221.4	225.6	230.0	233.9	235.5			
$E_{Filament}$, volts		4.8									
$I_{Filament}$, amps		16.0									
$I_{Coll.\ Heater}$, amps		8									
$I_{Res.\ Heater}$, amps		0									
Vacuum, 10^{-6} mm Hg		2.2	2.2	2.2	2.2	2.2	2.2	2.2			
~~Measured Efficiency, %~~		210.2	214.3	218.4	222.3	226.6	230.4	231.8			

NOTES: SHUT OFF AT END OF RUN TO REMOVE ADDED FINS.

THERMO ELECTRON
ENGINEERING CORPORATION

Converter No. T-205 Run No. 6 Observer P. Brosseau

VARIABLE		1	2	3	4	5	6	7	8	9	10
Date		10-21	10-21	10-21	10-21	10-21	10-21	10-21	10-21	10-21	10-21
Time		11:42	13:20	13:32	14:02	14:36	14:53	14:59	15:28	16:00	16:11
Elapsed Time, Hours		59.4	61.0	61.2	61.7	62.3	62.6	62.7	63.2	63.7	63.9
T_O, °C		1591				1591	1689				
T_O Corrected, °C		1588 †				1588†	1686 †				
$\Delta T_{Bell\ Jar}$, °C		12				12	14				
T_H, °C		1600 ←	—	1620†	→	1600	1700	←	1720†		→
ΔT_E, °C		21	22	24	27	40	23	25	28	37	47
T_E, °K		1872	1871	1869	1866	1853	1970	1968	1965	1956	1946
V_O, volts		1.4	1.2	1.0	0.8	0.6	1.4	1.2	1.0	0.8	0.6
I_O, amps		2.7	5.2	7.4	13.3	39.1	6.2	9.6	17.1	34.2	54.9
P_O, watts											
I-V Trace No.		—			*						
T_R	mv	11.3	11.6	12.2	12.5	13.5	12.3	12.6	12.9	13.7	14.3
	°C	278	285	300	307	331	302	309	317	336	350
	°K	551	558	573	580	604	575	582	590	609	623
T_C	mv										
	°C	508	529	551	590	740	590	610	655	752	855
	°K	781	802	824	863	1013	863	883	928	1025	1128
T_C base inner	mv										
	°C										
T_C base outer	mv										
	°C										
$T_{Radiator}$	mv	17.0	17.5	17.9	18.7	21.5	18.7	19.1	20.0	21.9	23.4
	°C	414	426	436	454	520	454	464	485	529	564
V_{eb}, volts		990	988	986	984	974	984	982	980	973	967
I_{eb}, mA		170	180	189	207	283	225	237	262	317	369
$E_{Filament}$, volts		4.7				5					
$I_{Filament}$, amps		16				17					
$I_{Coll.\ Heater}$, amps		0				0	0				
$I_{Res.\ Heater}$, amps		0.5	1.55	1.79	1.79	1.77	1.64	1.80	1.79	1.75	1.76
Vacuum, 10^{-6} mm Hg		2.4				2.5					2.6
Measured Efficiency, %											

NOTES: Pyrometer calibration 1693°C observed = 1690 true $\Delta T_{pyro} = -3$ †

* CONVERTER OUTPUT INCREASED STEPWISE AT 0.8 V.

† NOTE ADDED 11-1-66: PYROMETER CALIBRATION DATA WAS READ INCORRECTLY AND SHOULD BE: 1693°C OBS = 1710 true $\Delta T_{pyro} = 17$ °C – ALL EMITTER TEMPERATURES ARE 20° HIGHER THAN RECORDED ON PAGES 5 & 6 – T_E VALUES HAVE BEEN CORRECTED TO READ EXACT VALUE

THERMO ELECTRON
ENGINEERING CORPORATION

Converter No. T-205 Run No. 6 Observer P.P.[illegible]

VARIABLE		1	2	3	4	5	6	7	8	9	10
Date		10-21	10-21	10-21	10-21	10-21					
Time		16:52	17:01	17:12	17:22	17:40					
Elapsed Time, Hours		64.5	64.7	64.9	65.0	65.3					
T_O, °C		1787									
T_O Corrected, °C		1784 *									
$\Delta T_{Bell\ Jar}$, °C		16									
T_H, °C		1800 ←		1820*	→						
ΔT_E, °C		25	28	34	43	53					
T_E, °K		2068	2065	2059	2050	2040					
V_O, volts		1.4	1.2	1.0	0.8	0.6					
I_O, amps		10.0	16.8	28.9	47.0	66.2					
P_O, watts		14	20.4	28.9	37.6	39.7					
I-V Trace No.											
T_R	mv	13.0	13.1	13.6	14.3	15.0					
	°C	319	321	333	350	367					
	°K	592	594	606	623	640					
T_C	mv										
	°C	655	700	765	855	950					
	°K	928	973	1038	1128	1223					
T_C base inner	mv										
	°C										
T_C base outer	mv										
	°C										
$T_{Radiator}$	mv	20.1	20.7	21.9	23.5	25.0					
	°C	487	501	529	567	602					
V_{eb}, volts		979	976	971	965	958					
I_{eb}, mA		283	305	346	403	459					
$E_{Filament}$, volts		5									
$I_{Filament}$, amps		17									
$I_{Coll. Heater}$, amps		0									
$I_{Res. Heater}$, amps		1.67	1.71	1.71	1.65	1.59					
Vacuum, 10^{-6} mm Hg		2.3				3.0					
Measured Efficiency, %											

NOTES: * see previous page, note †.